

Cost-Effective Design Techniques for Electronics Reliability

Charles T. Leonard/Boeing Commercial Airplane Group

Improved reliability is achieved through passive cooling, accommodating higher temperatures, changing part selection and derating criteria, environmental stress screening, and analyzing equipment failures to determine the real cause.

The usual process of designing for reliability involves a preliminary reliability prediction and subsequent design modifications to improve the calculated results. The major elements of the process involve temperature, part count, device quality level, and similar considerations. The predictive methodology is intended to portray the various failure acceleration stresses, which are then often used in the reverse direction to improve the expected results. The concepts of predictive methodology as related to electronics reliability appear widely without full disclosure as to source, and their application without serious scrutiny can impose major increased costs beyond identifiable benefit.

Temperature is treated with great respect in the design of electronic equipment, especially in applications where long-term reliability is needed. In some cases the temperature influence on reliability is inarguable—cases where temperature is directly related to parameter drift, premature aging, and even catastrophic failures. Examinations of case histories indicate that temperature's relationship to reliability may be more a case of exposing incompatibilities between operational requirements and design or manufacturing processes. In other words, the product as

designed is not suitable for operation in the desired environment without changes. In such cases certain questions must be addressed before taking action:

- Will lowered temperature by itself avoid the experienced failures? If so, how much should it be lowered and how is the conclusion reached?

- Should the root cause of the failure be identified and addressed?

Each action has its own costs, and the designer or user must fully understand the implications of each to produce cost-effective, reliable equipment. Understanding the role of temperature may be difficult even after close scrutiny.

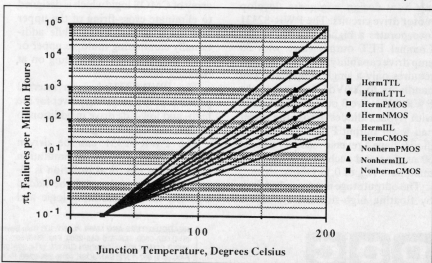


Figure 1. Typical Representation of Failure Acceleration of Components Due to Temperature. This is a plot of the πT factor tabulated in MIL-HDBK-217 for various classes of parts. (Curve does not appear in MIL-HDBK-217 for obvious reasons. It is not "real world.") It should not be accepted without question.

In the majority of cases studied where there was apparent statistical agreement between failures and temperature, and where temperature was initially blamed for the failures, effective corrective action involved changes in design or manufacturing techniques, or both, often leaving temperature essentially unchanged. Accommodation of temperature in some applications can be more cost effective than lowering temperature, and the decision is one that should be considered carefully, weighing some complex interacting factors.

Because of the strong influence attributed to temperature, major efforts are routinely accepted to reduce temperature.

Calculated results are routinely used as though they result from tests and as though they present an accurate model of the temperature-related reliability of devices. They do not.

A rational approach to temperature and cost-effective reliability should contain several elements in sequence:

- Determination of an upper limit temperature based on actual undesired effects of temperature that must be avoided
- Comparison studies to arrive at techniques, with alternatives, of ways not to exceed the upper limit temperature by circuit design and use of cooling systems
- Studies to determine results at even higher temperature, with the possible redesign and component selection implications that may be involved

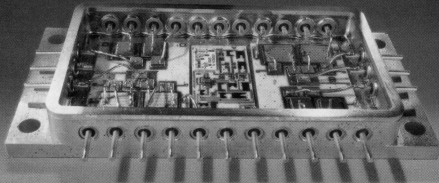
A rational approach to the temperature/design/component selection interactions can sometimes lead to improved economies and system simplifications. Often, by subjecting the questions to skeptical review new options become visible.

Failure Prediction Methodology (FPM)^[1] presents explanations of failures of electronic devices. In most of its appearances, the format of FPM is expressed mathematically as:

$$\lambda_{\text{box}}^{[2]} = \sum \lambda_{\text{parts}}, \text{ and}$$

$$\lambda_{\text{part}} = \lambda_{\text{base}} (\pi_Q \cdot \pi_T \cdot \dots),$$

where λ = failure rate, π = failure accelerator due to quality, π_T = failure



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At 25°C

300

Beryllia

200

Aluminum Nitride

100

Boron Nitride

Alumina

At 125°C

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accelerator due to temperature, etc., and $\pi_T = A e^{(T)}$.

The temperature ingredient in the reliability equation appears in many guises, not always adequately identified as to source. Electronics parts manufacturers may present curves of failures versus operating temperature, and the curves often generally follow the exponential influence representations fundamental to FPM, as shown in Figure 1. Such failure vs

Power consumption for the cooling machinery has also increased with time, such that the cooling power consumption in some cases has exceeded the power consumption of the electronics being cooled!

temperature representations may be without experimental validation beyond a few data points at a high stress situation. Commonly, a small number of failures at high temperature are extrapolated to more moderate operating conditions using the Arrhenius or Eyring relationships. Calculated results are routinely used as though they result from tests and as though they present an accurate model of the temperature-related reliability of devices. They do not.

Effects of Military Practices

Suppliers to the military often have little latitude in their design decisions. Their techniques for achieving reliability often commence with a mandated reliability prediction whose format and calculation factors may be specified. They must comply with rigid specifications in such matters as selection of component parts, fabrication processes and materials, and other details that would be a part of a designer's judgment in other industries. Virtually the only variable a designer may influence is temperature. The system designer (as for example in a helicopter program) may perform trade studies of power consumption and weight as penalties that are balanced off against calculated reliability of electronics. A lower coolant temperature generally costs more weight and power, but allows lower operating

temperature for electronics. Or, a lower coolant temperature can permit smaller and lighter electronics because of a higher allowable temperature rise within the black boxes themselves, offsetting to some degree the weight involved in providing the lower temperature coolant. When mandated for use in system design, FPM supplies its own credibility for the methodology. Numerical manipulations within the assumption framework of FPM are usually accepted without serious question or scrutiny.

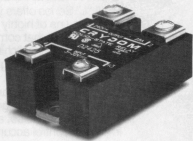
Because of the narrow range of available decisions in military applications, the field of Reliability Engineering employs mathematicians and statisticians who concern themselves with the complex analytical issues of manipulating variables within the framework of the FPM concepts. A review of papers at recent reliability engineering conferences and papers published in the journals, indicates the wide interest in the statistical aspects of failure events using FPM as the assumption base, in lieu of actual investigations of failures and actions to correct root causes of failures. The value of such activities should be closely reviewed and possibly redirected closer to actual efforts intended to understand and avoid failures and eliminate causes of failures.

In the usual military programs, the ingredient of cost-effectiveness of reliability improvements seldom appears with any seriousness. The first goal is to demonstrate compliance with specified reliability, and that demonstration often emanates from the reliability prediction. Until that demonstration (usually a calculation result) has been concluded, there can be no realistic consideration of cost-effectiveness, for no contract will be issued without specification compliance. Designers have little latitude to perform realistic trade studies to evaluate design options, for the usual case is that even the format and the calculation factors for reliability evaluations are specified, along with specifications for the required components. Later considerations to improve costs may be relatively trivial in effect, and even then, subject to long and tedious negotiations with no guaranteed outcome to justify the effort.

Military procurements have constraints that are not common to the wider electronics industry. However, it must not be concluded that only the military/aviation applications stray into cooling complexities without adequate definition of actual need. Many personal computers are equipped with small cooling fans to lower temperatures within the computer housing. Several techniques for passive cooling (described later), if applied at the time of preliminary packaging design, could produce internal temperatures similar to the temperatures resulting from use of a

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fan. In this respect, the fan must be regarded as a bandage for a self-inflicted wound. The price of the fan is small and is paid by the user in terms of increased operating noise and a small price increment.

Diagnoses of Failures

In the interest of brevity, the following data are presented in summary form. They are the results of studies of failure examinations of boxes removed from service. The impressive point of the investigations was the regularity of the diagnosis conclusions, virtually independent of the type of box, its application, or any of the other variables. Upon close examination, the dominant root causes of box removals were human-related events: workmanship, design, unjustified removals, etc. A failure truly attributable to a component part failure was a rare event indeed.

One must be careful with concepts and definitions. Investigations must be complete to identify clearly the root cause of failure, and the conclusions must take a narrow view of a part failure. The following events did not satisfy the criteria for a part failure, being related to avoidable events, human related:

- Inadequate diagnosis
- Improper part for the application
- Electrostatic damage
- Damage during installation or later handling
- Poor solder joint
- Voltage spike

Widely differing classes of equipment, used in many applications, often display similarities in failure diagnoses. Several

thousand box removals were scrutinized in detail, and the pattern was revealing in that clearly the failure-avoidance activities extracted from FPM were not describing the failures that were being experienced. The summary is depicted in *Figure 2*.

Thorough examination of failures is a mandatory ingredient for effective corrective actions to avoid similar events in the future. Not only in the interests of product quality, but as a cost reduction technique, diagnosis and root cause correction must be viewed as mandatory. The results can be illuminating. Where FPM describes parts as being the major source of problems, a comprehensive diagnosis effort may provide a different view, simultaneously leading to more reliable products for the future and often dramatically reduced costs. Such was our experience at Boeing.

Other visions of temperature's influence concern infant mortality failures. Only too often, a failure is simply repaired and the box returned to service; later production units continue to be shipped with the same sources for potential failure. Burn-in, where equipment is operated for extended periods at elevated temperature to uncover latent defects, is a commonly used production activity. And if equipment that has been burned-in continues to experience early failures, the burn-in period sometimes will be extended in the hopes of accelerating the latent flaws to failure while the equipment is still on the bench. Such measures, derived from the temperature/stress concepts of FPM, are often time consuming and yield marginal, but expensive, benefit. When failed items are diagnosed fully, the failure corrections usually require design or process changes, for the usual failures are more mechanical in nature. An effective infant mortality reduction program requires rapid temperature cycling over a fairly wide range,

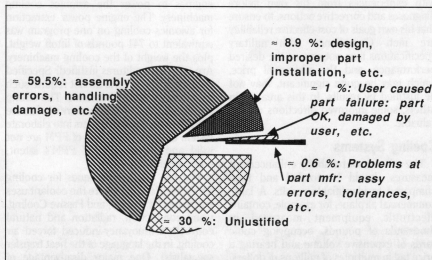


Figure 2. Summary of Diagnoses of Boxes That Were Removed From Service.

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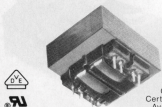
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combined with random vibration. When coupled with an effective corrective action program to avoid repetition of future similar failures, the process can be highly cost-effective and can lead to continuing product improvement. The techniques are often referred to as Environmental Stress Screening and may require much less process flow time than burn-in. This is a developing technology field that can be valuable for producing high quality equipment at lower cost. The goal should be one of eliminating causes of failures so that production flow screens are used only to ensure that processes are maintained in close control.

Electronic part quality can play an important role in cost-effective reliability considerations. Device quality has improved dramatically over the years such that high quality components at low price are

readily be attributed to activities intended to enhance the reliability of electronics. Such a significant price requires equally significant benefits.

An example of part of the price of reliability can be seen in airborne cooling systems. As more dependence is placed on properly functioning electronics, the cooling systems have grown in complexity, as shown in Figure 3.

In addition to the weight and complexity increase of the cooling systems, power consumption for the cooling machinery has also increased with time, such that the cooling power consumption in some cases has exceeded the power consumption of the electronics being cooled! Thermal design considerations within the boxes, such as heat spreaders, wider spacings between circuit boards for better airflow, card edge heat transfer measures, etc., add up so that the total of identifiable temperature-related considerations involves several hundred pounds and a significant

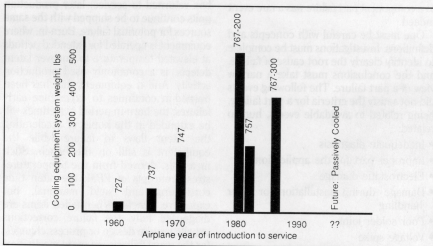


Figure 3. Weight Growth of Avionics Cooling Systems for Commercial Airplanes.

available from many sources. The designer's responsibility is to use judgment, tempered with experiences from his own failure diagnoses and corrective actions, to ensure that his own goals of cost-effective reliability are met. Compliance with military specifications may not ensure the desired performance, and the additional price, which may be quite significant, may not be justified by results. In this area, as in others, some improved directions can be valuable.

Cooling Systems

The full cost of reliability enhancement measures should be totaled and then compared to identifiable results. A large commercial airplane, for example, contains electronic equipment measured in thousands of pounds, occupying cubic yards of expensive volume and bearing a price tag in multiples of millions of dollars. A significant fraction of the penalties can

increase in equipment volume. A military helicopter uses power from the turbine engines to power the avionics cooling machinery. The engine power extraction for avionics cooling on one program was equivalent to 741 pounds of liftoff weight, plus the weight of the cooling machinery. Are such expenditures justified? Specified military design criteria do not require such solutions except by inference. The strong representations of temperature's influence in FPM often guide designers into elaborate system designs. Such uses of FPM are not valid and are misuses of FPM's intent, purpose and authority.

The two major techniques for cooling are Active Cooling, where the coolant uses machinery for motion, and Passive Cooling, using conduction, radiation and natural convection (buoyancy-induced forced air cooling, in the language of the heat transfer specialists). One major disadvantage of active cooling is that once incorporated,

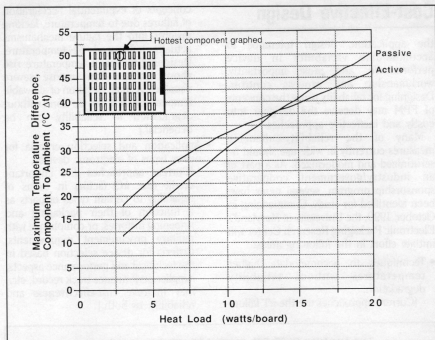


Figure 4. Active vs Passive Cooling Test Results. The actively cooled boards are provided with cooling air at the rate of 8 lb/KW-minute, and the passively cooled boards use only natural convection. All boards are vertically mounted with ventilating holes in the top and bottom casings.

the equipment so cooled may be dependent upon its cooling system's operation for its own survival, thus introducing another source of overall unreliability. Combined with the other prices of active cooling, passive cooling is attractive in many cases.

A laboratory experimental and analytical development program^[3,4] explored the application feasibilities of passive cooling. Heat transfer effectiveness comparisons were made for circuit boards of similar configuration, mounted vertically with air flowing upwards across the components on the boards. In general, results indicated that the following simplified rules should be observed for best heat transfer (maximum wattage dissipated for a given limit temperature, or minimum temperature for a given wattage):

- Mount circuit boards vertically with long dimension horizontal
- Provide unrestricted free air passageways between circuit boards
- Provide adequate ventilating holes top and bottom
- Install high wattage components along bottom edge and low wattage devices at the top.

Figure 4 shows results of a test board whose components have equal dissipation cooled both actively and passively. The temperature of the hottest component (center, in top row) is represented.

Component arrangement has an important influence on heat transfer for

passively cooled boards where the cooling air flows across the components and the boards are mounted vertically. When all the components of the same test board as in Figure 4 are operated at uniform power density, the resultant temperatures as a function of placement are depicted by Figure 5. Note that the hottest components (center, top row) exceeded a 60°C temperature rise, with the power to the board at 25W.

The same board with its power dissipation a variable depending upon device placement, is able to dissipate more power at a lower maximum component temperature. Figure 6 shows that it was able to dissipate more power (28W vs 25W) than the board with uniform power to all elements, and the hottest element was cooler. All elements operated at 50°C temperature rise. Additional reliability is achieved because uniform temperature across the board will reduce thermal gradient stresses and thus improve fatigue life of connections.

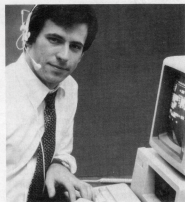
Combining the results of several tests, the curves of Figure 7 are useful for comparisons of heat transfer techniques.

Future Directions

By considering thermal aspects early in the design process, a designer can use simple concepts to avoid excessive temperatures that could reduce reliability. Close attention must be paid to other elements such as component selection for

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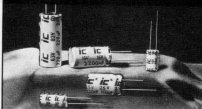
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the application, design tolerance to accommodate variability in device performance, and most importantly, workmanship and process controls. Designing for reliability using the concepts of FPM may deceive the designer into costly and ineffective approaches.

Many of the reliability-enhancing measures currently in wide use should be scrutinized and modernized. As a part of an industry/government cooperative sponsorship program, several items have been identified for study. Commencing in October, 1990, the University of Maryland's Electronic Packaging Research Center will initiate effort in the following areas:

- Techniques to accommodate higher temperatures without reliability degradation.

[Current approaches use the πT failure

concepts of exponential acceleration of failures due to temperature, lacking insights into the failure mechanisms actually influenced by temperature. Designing for small temperature rise above ambient can impose severe penalties. A small elevation of allowable temperature, if it can be done without degradation in reliability, can be beneficial.]

- Application and selection criteria for newer types of electronic devices.

[Current approaches give important credit (the πQ factor) in terms of reliability to certain types of parts as a function of their packaging and screening histories, or compliance with military procurement requirements. Criteria for device selection based in the technical and performance aspects, supplier performance track record, etc., may improve cost-effectiveness and reliability, or both.]

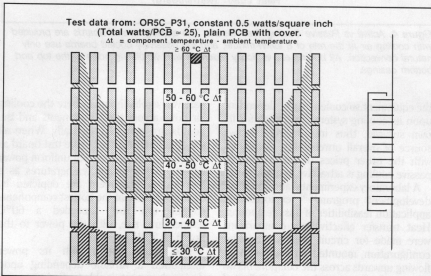


Figure 5. Temperatures of Board-Mounted Components, Passively Cooled, With the Power Dissipation Uniformly at 0.5W/Square Inch.

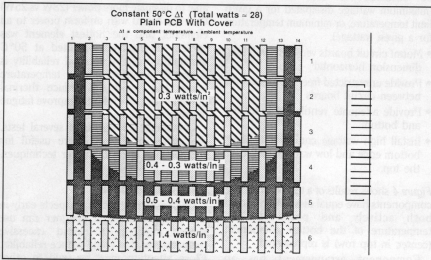


Figure 6. Component Arrangement for Constant Temperature, Passively Cooled.

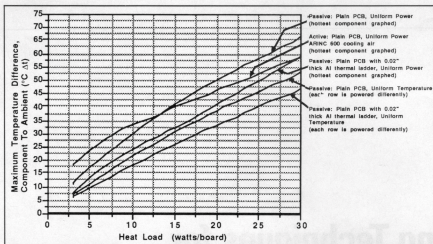


Figure 7. Summary of Test Results On Circuit Boards With Active and Passive Cooling, Some With Heat Transfer Enhancements.

- Passive cooling for electronics in lieu of the widely used active cooling.

[Current industry standards for airborne electronics generally focus on cooling system design with little insight into alternatives. Prior Boeing research indicates the value of Passive Cooling as a means of system simplification and cost-effectiveness improvement. These techniques need further study for wider application.]

- Derate criteria for selection and application of electronic parts, based on device technology and application considerations.

[Current derate criteria generally originate in the concepts of FPM and combine temperature with power level, using Arrhenius and Eyring extrapolations. Such approaches are believed to be unnecessarily conservative.]

- An improved methodology for estimating the future inservice reliability performance of assemblies, replacing the current concept of a constant failure rate of devices, with failure rates increased by environmental and operational stresses.

[Current approaches often use the prediction techniques of FPM. There is often little correlation between predicted and actual events, either as to failure mode or failure frequency, resulting in misguided efforts to design for reliability and cost-effectiveness. In general, FPM predicts events that do not happen and does not predict the events that do happen. An error-filled reliability prediction calls into question every downstream decision based on FPM's methodology.]

- Comprehensive plans for Environmental Stress Screening.

[The developing technology of

Environmental Stress Screening holds promise, not only as a technique aiding the goal of defect-free products, but also as a tool for significant cost reductions in manufacturing by virtue of reduced rework due to early identification of fabrication problem areas. Additionally, the techniques and equipment developed for ESS can provide a tool for design validation and early assessment of anticipated inservice reliability performance when used as a design tool.]

Charles T. Leonard is a Mechanical Engineer graduate of Texas Technological University. He is employed by Boeing Commercial Airplane Group in the Directorate of Electronics Engineering, where he has the task of improving the technology base for electronic equipment in hardware topics. Leonard has published several papers in engineering journals and has participated in engineering conferences discussing the topics of cost-effective electronics design.

Notes/References

1. Failure Prediction Methodology discussions in this paper apply to any of the methodologies for predicting reliability of electronic equipment that contains the concepts of constant failure rate accelerated by stresses such as temperature. They often present a data base and tabulated failure acceleration factors, encouraging mathematical manipulations to yield products with a desired calculated reliability. The USAF document MIL-HDBK-217 is the most popularly accepted example of FPM.
2. For the purposes of this paper, "box" refers to any electronic assembly that is a separate deliverable or line replaceable unit. It may or may not have its separate enclosure, for it may be a circuit board within a system enclosure.
3. "Passive Cooling for Avionics Can Improve Airplane Efficiency and Reliability," National Aerospace Electronics Conference, Dayton, May, 1987.
4. "Passive Cooling for Avionics," Presented at AEEC Conference, Los Angeles, Oct 87. □

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